

# Chemical analysis of CH stars - II: atmospheric parameters and elemental abundances

Drisya Karinkuzhi<sup>1,2</sup>, Aruna Goswami<sup>1</sup>

<sup>1</sup>Indian Institute of Astrophysics, Koramangala, Bangalore 560034, India; drisya@iiap.res.in, aruna@iiap.res.in

<sup>2</sup>Department of physics, Bangalore university, Jnana Bharathi Campus, Karnataka 560056, India

Accepted —; Received —; in original form —

## ABSTRACT

We present detailed chemical analyses for a sample of twelve stars selected from the CH star catalogue of Bartkevicius (1996). The sample includes two confirmed binaries, four objects that are known to show radial velocity variations and the rest with no information on the binary status. A primary objective is to examine if all these objects exhibit chemical abundances characteristics of CH stars, based on detailed chemical composition study using high resolution spectra. We have used high resolution ( $R \sim 42000$ ) spectra from the ELODIE archive. These spectra cover 3900 Å to 6800 Å in the wavelength range. We have estimated the stellar atmospheric parameters, the effective temperature  $T_{eff}$ , the surface gravity  $\log g$ , and metallicity  $[Fe/H]$  from LTE analysis using model atmospheres. Estimated temperatures of these objects cover a wide range from 4200 K to 6640 K, the surface gravity from 0.6 to 4.3 and metallicity from  $-0.13$  to  $-1.5$ . We report updates on elemental abundances for several heavy elements, Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm, Eu and Dy. For the object HD 89668 we present the first abundance analyses results. Enhancement of heavy elements relative to Fe, a characteristic property of CH stars is evident from our analyses in case of four objects, HD 92545, HD 104979, HD 107574 and HD 204613. A parametric model based study is performed to understand the relative contributions from the s- and r-process to the abundances of the heavy elements.

**Key words:** stars: Abundances - stars: Carbon - stars: Late-type - stars: Population II.

## 1 INTRODUCTION

CH stars are characterized by iron deficiency and enhancement of Carbon and s-process elements. Majority of the CH stars are known as binaries with white dwarf companions that are presently not visible (McClure 1983, 1984, McClure & Woodsworth 1990). The companion white dwarfs produced heavy elements while passing through the AGB stage of evolution; these material are received by the CH stars through mass transfer enriching their surface chemical composition. CH stars thus provide an important means to study the production and distribution of heavy elements arising from AGB nucleosynthesis.

In spite of their usefulness, literature survey reveals that detailed chemical composition studies are not available for many CH stars. The CH star catalogue of Bartkevicius (1996) lists about 261 objects, 17 of which belong to  $\omega$  Cen globular cluster. Many of the objects listed in this catalogue have no information on binary status.

It would be interesting to compare and examine the abundance patterns of elements observed in the confirmed

binaries with their counterparts in objects that have no information on binary status. While long-term radial velocity monitoring are expected to throw light on the binary status, detailed chemical composition studies could also reflect on the binary origin.

Previous studies along this line include a detailed chemical composition study of ten objects from the Bartkevicius catalogue by Karinkuzhi & Goswami (2014) (paper 1). This study revealed that only five objects out of ten, exhibit abundances of heavy elements with  $[Ba/Fe] > 1$ , a characteristic of CH stars. Four objects show either near-solar values or  $[Ba/Fe] < 0$ . The remaining one object, HD 4395 gave  $[Ba/Fe] \sim 0.79$ . Based on their analyses the authors concluded that out of ten, only five objects are bonafide CH stars.

As far as the chemical composition is concerned, CH stars (with  $-0.2 < [Fe/H] < -2$ ) and the class of carbon-enhanced metal-poor (CEMP)-s ( $[C/Fe] > 1$ ,  $[Fe/H] < -2$ ; Beers and Christlieb 2005) stars are believed to have a similar origin. Medium resolution spectral analyses of about 300

faint high latitude carbon stars of Hamburg/ESO survey (Christlieb et al. 2001) have shown that about 33 per cent of the objects are potential CH star candidates (Goswami 2005, Goswami et al. 2007, 2010a). Analyses of high resolution Subaru spectra for a sample of them, have shown the object HE 1152–0355 to be a CH star, and HE 1305+0007, a CEMP-r/s star (Goswami et al. 2006). A large fraction of CEMP-s and CEMP-r/s stars show radial velocity variations, based on which these stars are suggested to be all binaries (Lucatello et al. 2005), and that the CEMP-s stars are the more metal-poor counterparts of CH stars.

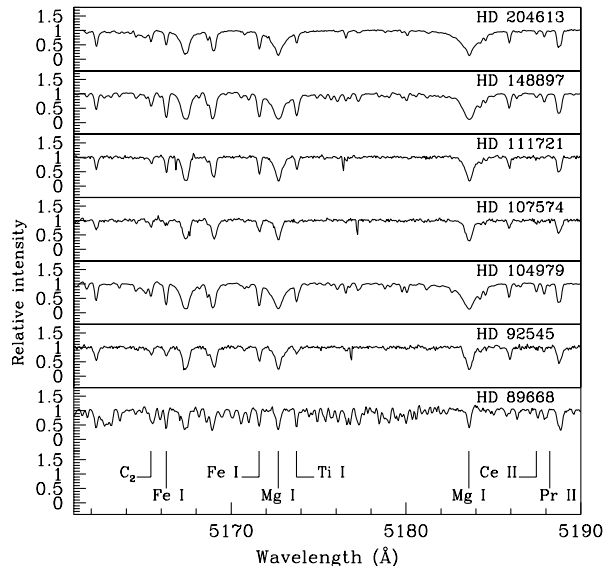
Although high resolution spectroscopic analyses of CEMP stars have shown that a variety of production mechanisms are needed to explain the observed range of elemental abundance patterns in them, it is widely accepted that the binary scenario of CH star formation is the most likely formation mechanism also for CEMP-s stars (Barbuy et al. 2005; Norris et al. 1997a, b, 2002; Aoki et al. 2001, 2002a,b, 2007; Lucatello et al. 2005; Goswami et al. 2006, Goswami & Aoki 2010b).

In this work we have considered another twelve objects from the catalogue of Bartkevicius (1996) for a detailed chemical composition study. Detailed high resolution spectroscopic analyses for this sample of objects are either not available in the literature or limited by resolution or wavelength range. Polarimetric studies of carbon stars by Goswami & Karinkuzhi (2013) include six objects from this sample. Among these three objects show percentage V-band polarization at a level  $\sim 0.2$  per cent (HD 55496 ( $p_v$  per cent  $\sim 0.18$ ), HD 111721 ( $p_v$  per cent  $\sim 0.22$ ), and HD 164922 ( $p_v$  per cent  $\sim 0.28$ )) indicating presence of circumstellar dust distribution in non-spherically symmetric envelopes. The other three objects, HD 92545, HD 107574 and HD 126681, show V-band percentage polarization at a level  $< 0.1$  per cent.

The sample of programme stars includes two confirmed binaries, HD 122202 and HD 204613. Four objects in this sample, HD 55496, HD 92545, HD 104979 and HD 107574 are known to show radial velocity variability, and for the rest, none of these two information is available. In the following text, for convenience, we will refer the objects that are confirmed binaries as group one objects, those with limited radial velocity information as group 2 objects and the objects for which none of these information are available as group three objects. One of our primary objectives is to estimate the abundances of heavy elements and critically examine the abundance patterns and abundance ratios to check if they exhibit characteristic abundance patterns of CH stars.

Among CEMP stars the group of CEMP-r/s stars show enhancement of both r- and s-process elements ( $0 < [\text{Ba}/\text{Eu}] < 0.5$  (Beers & Christlieb 2005)). None of our objects in the sample are found to show  $[\text{Ba}/\text{Eu}]$  ratios in this range. Four objects show characteristic heavy element abundance patterns of CH stars. Based on our analyses, the others certainly do not belong to this class of objects.

Source of the high resolution spectra is described in section 2. Estimates of radial velocities are presented in section 3. Temperature estimates from photometry are discussed in section 4. Estimation of stellar atmospheric parameters are presented in section 5. Results of abundance analysis are discussed in section 6. In section 7 we present brief dis-



**Figure 1.** Sample spectra of a few programme stars in the wavelength region 5160 to 5190 Å,

cussions on each individual star. Estimated stellar masses are discussed in section 8. A discussion on the parametric model based analysis is presented in section 9. Conclusions are drawn in section 10.

## 2 SPECTRA OF THE PROGRAMME STARS

Low-resolution spectra of these objects obtained from 2m Himalayan Chandra Telescope at the Indian Astronomical Observatory (IAO), Hanle using HFOSC clearly show strong features due to carbon. HFOSC is an optical imager cum spectrograph for conducting low- and medium-resolution grism spectroscopy (<http://www.iap.res.in/iao/iao.html>). High resolution spectra necessary for abundance analyses of the programme stars are taken from the ELODIE archive (Moultaka et al. (2004)). This archive contains a large collection of high-resolution spectra acquired with the 1.93 m telescope at the Observatoire de Haute Provence (OHP) using the ELODIE spectrograph (Baranne et al. 1996). An online reduction software program TACOS automatically performs optimal extraction and wavelength calibration of data. The spectra consist of 67 orders with near constant inter order spacing. The resolution of the spectra is  $\sim 42000$  and cover the wavelength range 3900 Å to 6800 Å. A few sample spectra are shown in Figures 1 and 2. The basic data for the programme stars obtained from the SIMBAD database are listed in Table 1.

## 3 RADIAL VELOCITY

Radial velocities of the programme stars are calculated using a selected set of clean unblended lines in the spectra. Estimated mean radial velocities along with the standard deviation of the mean values are presented in Table 2. The literature values are also presented for a comparison. Reports on

Table 1: Basic data for the programme stars

Star Name.	RA(2000)	DEC(2000)	B	V	J	H	K
HD 55496	07 12 11.37	-22 59 00.61	9.30	8.40	6.590	6.043	5.931
HD 89668	10 20 43.40	-01 28 11.38	10.50	9.41	7.443	6.908	6.760
HD 92545	10 40 57.70	-12 11 44.23	9.07	8.56	7.548	7.347	7.282
HD 104979	12 05 12.54	+08 43 58.74	5.10	4.13	2.459	1.987	1.869
HD 107574	12 21 51.86	-18 24 00.15	8.99	8.54	7.660	7.460	7.415
HD 111721	12 51 25.19	-13 29 28.17	8.78	7.97	6.347	5.898	5.786
HD 122202	14 00 18.96	+04 51 25.06	9.85	9.36	8.506	8.358	8.252
HD 126681	14 27 24.91	-18 24 40.43	9.93	9.32	8.044	7.709	7.631
HD 148897	16 30 33.54	+20 28 45.07	6.50	5.25	2.950	2.248	1.966
HD 164922	18 02 30.86	+26 18 46.80	7.79	6.99	5.553	5.203	5.113
HD 167768	18 16 53.10	-03 00 26.64	6.89	6.00	4.376	3.906	3.789
HD 204613	21 27 42.96	+57 19 18.86	8.86	8.22	7.100	6.824	6.788

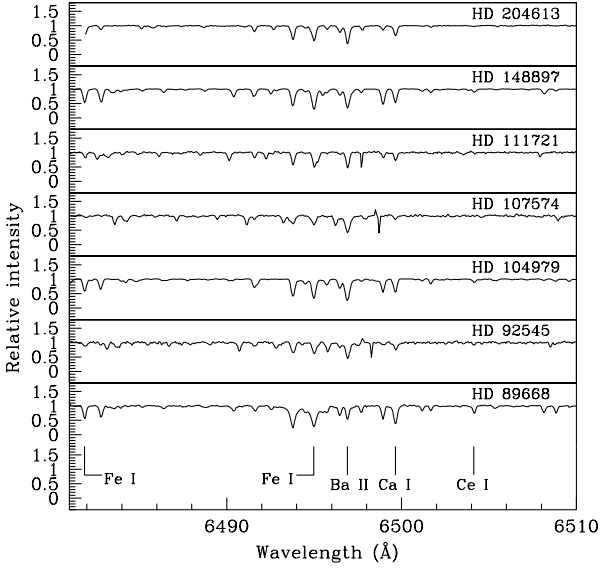


Figure 2. Spectra showing the wavelength region 6480 to 6510 Å, for the same stars as in Figure 1.

radial velocity variations for a large number of CH and barium stars are available in literature (McClure (1984, 1997) and McClure and Woodsworth (1990)). McClure (1997) has reported the radial velocity variations and orbital parameters for two sub-giant CH stars HD 122202 and HD 204613. These objects are confirmed binaries. Although radial velocity variations are noticed in HD 55496, it is not confirmed as binary. Our estimate also shows a difference of  $7 \text{ Kms}^{-1}$  from the literature value. Mild radial velocity variations are also noticed in HD 92545 and HD 107574 (North et al. 1992). Our radial velocity estimates of HD 104979 and HD 164922 show a difference of  $\sim 15 \text{ Kms}^{-1}$  from the literature values.

#### 4 TEMPERATURES FROM PHOTOMETRIC DATA

Temperatures from photometric data are estimated following the procedure discussed in paper I. Here we mention a few points relevant to the present work. Colour-temperature calibrations of Alonso et al. (1996) are used for photometric temperature determination. These calibrations were derived

by using a large number of lower main-sequence stars and sub-giants, whose temperatures were measured by the infrared flux method, and hold within temperature and metallicity ranges of  $4000 \text{ K} \leq T_{\text{eff}} \leq 7000 \text{ K}$  and metallicity between  $-2.5$  and  $0.0$ . The uncertainty in the temperature calibrations is  $\sim 100 \text{ K}$ . Although the difference between 2MASS infrared photometric system and photometry data measured on the TCS (Telescopio Carlos Sanchez) system used by Alonso et al. to derive the  $T_{\text{eff}}$  scales is very small, we have used the necessary transformations between the different photometric systems from Ramirez and Melendez (2004) and Alonso et al. (1996, 1999). The equations are:

$$J_{TCS} = J_{2MASS} + 0.001 - 0.049(J_{2MASS} - K_{2MASS})$$

$$H_{TCS} = H_{2MASS} - 0.018 + 0.003(J_{2MASS} - K_{2MASS})$$

$$K_{TCS} = K_{2MASS} - 0.014 + 0.034(J_{2MASS} - K_{2MASS})$$

$$K_J = K_{TCS} + 0.042 - 0.019((J_{TCS} - K_{TCS}) - 0.008)/0.910$$

$$(V - K)_{TCS} = 0.050 + 0.993(V - K_J)$$

$$\theta_{JK} = 0.582 + 0.799(J_{TCS} - K_{TCS}) + 0.085(J_{TCS} - K_{TCS})(J_{TCS} - K_{TCS})$$

$$\theta_{JH} = 0.587 + 0.922(J_{TCS} - H_{TCS}) + 0.218(J_{TCS} - H_{TCS})(J_{TCS} - H_{TCS}) + 0.016(M)(J_{TCS} - H_{TCS})$$

$$\theta_{VK} = 0.555 + 0.195(V - K)_{TCS} + 0.013(V - K)_{TCS}(V - K)_{TCS} - 0.008(V - K)_{TCS}(M) + 0.009(M) - 0.002M^2$$

$$T_{EFF(xy)} = 5040/\theta_{(xy)}$$

where  $M$  is the metallicity of the star,  $xy$  indicates the JK, JH and VK. For two objects temperatures derived from both spectroscopic method and photometric method are similar. Among the rest for most of the objects the derived  $T_{\text{eff}}$  from V-K is  $\sim 350 \text{ K}$ , and from J-H is  $\sim 300 \text{ K}$  less than the adopted spectroscopic  $T_{\text{eff}}$ . The temperature calibrations from the  $T_{\text{eff}} - (J - H)$  and  $T_{\text{eff}} - (V - K)$  relations involve a metallicity ( $[\text{Fe}/\text{H}]$ ) term. Estimates of  $T_{\text{eff}}$  at four assumed metallicity values (shown in parenthesis) are listed in Table 3.

Table 2: Radial velocities

Star Name	$V_r$ km s $^{-1}$ our estimates	$V_r$ km s $^{-1}$ from literature	Reference
HD 55496	$315.28 \pm 0.80$	322.00	1
HD 89668	$22.84 \pm 0.70$	23.0	2
HD 92545	$-17.51 \pm 0.65$	-16.65	3
HD 104979	$-45.40 \pm 0.42$	-29.62	4
HD 107574	$-16.33 \pm 0.72$	-29.40	1
HD 111721	$20.59 \pm 0.67$	21.40	1
HD 122202	$-7.40 \pm 0.97$	-10.5	6
HD 126681	$-45.36 \pm 0.46$	-45.58	7
HD 148897	$17.55 \pm 0.71$	18.40	1
HD 164922	$34.86 \pm 0.91$	20.29	8
HD 167768	$1.39 \pm 0.42$	1.60	1
HD 204613	$-89.53 \pm 0.33$	-90.96	5

1. Goncharov (2006), 2. Soubiran et al. (2008), 3. Siebert et al. (2011), 4. Massarotti et al. (2008), 5. Pourbaix et al. (2004),  
6. Luck and Bond (1991), 7. Santos et al. (2011), 8. Nidever et al. (2002)

Table 3: Temperatures from photometry

Star Name	$T_{eff}$ (J-K)	$T_{eff}(-0.5)$ (J-H)	$T_{eff}(-0.5)$ (V-K)	$T_{eff}(-1.0)$ (J-H)	$T_{eff}(-1.0)$ (V-K)	$T_{eff}(-1.5)$ (J-H)	$T_{eff}(-1.5)$ (V-K)	$T_{eff}(-0.5)$ (B-V)	$T_{eff}(-1.0)$ (B-V)	$T_{eff}(-1.5)$ (B-V)	Spectroscopic estimates
HD 55496	4542.90	4441.94	4502.61	4458.65	4487.14	4475.49	4475.76	4774.22	4668.96	4591.12	4850
HD 89668	4462.68	4502.02	4518.76	4535.63	4318.91	4302.05	4288.96	4339.62	4246.01	4175.29	5400
HD 92545	6343.00	6422.81	6088.75	6436.34	6095.01	6449.92	6108.68	6159.33	6014.42	5914.10	6380
HD 104979	5025.77	5056.49	4896.90	5073.13	4885.21	5089.87	4878.30	4604.59	4503.92	4428.86	5060
HD 107574	6605.48	6892.23	6774.10	6903.73	6795.30	6915.27	6825.87	6847.21	6681.19	6569.80	6250
HD 111721	-	4601.48	6451.12	4618.25	6464.85	4635.14	6486.97	5011.10	4899.33	4817.63	5212
HD 122202	6417.84	6878.47	6890.04	6901.64	6370.16	6382.14	6402.28	6329.12	6179.09	6076.03	6430
HD 126681	5539.93	5508.00	5524.06	5540.22	5452.94	5448.38	5449.71	5629.53	5500.24	5408.49	5760
HD 148897	3635.13	3885.78	3762.86	3901.90	3743.08	3918.15	3726.27	4015.00	3929.84	3864.45	4285
HD 164922	5412.07	5422.44	5191.94	5438.65	5183.77	5454.94	5180.94	5038.84	4926.30	4844.15	5400
HD 167768	4841.08	4060.94	4910.98	4077.32	4899.44	4093.83	4892.70	4799.45	4693.50	4615.26	5070
HD 204613	6070.18	5869.04	5841.82	5884.32	5843.53	5899.68	5852.03	5494.19	5368.80	5279.24	5875

The numbers in the parenthesis indicate the metallicity values at which the temperatures are calculated. Temperatures are given in Kelvin

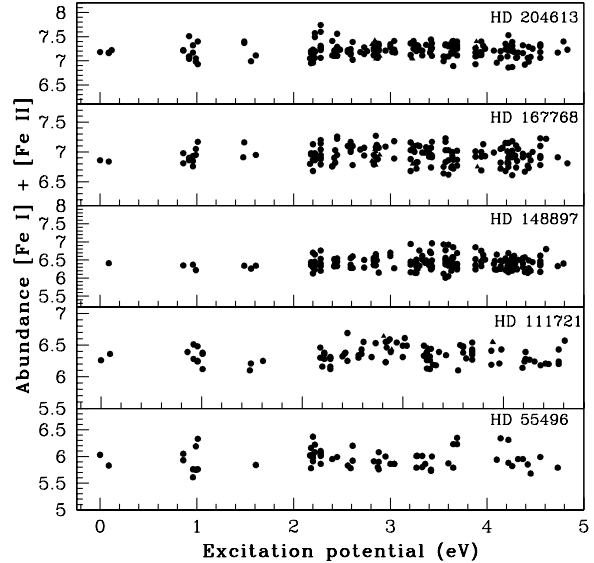
## 5 STELLAR ATMOSPHERIC PARAMETERS

The set of Fe I and Fe II lines used for the present analysis to find the stellar atmospheric parameters are listed in Tables 4A and 4B. The excitation potential of the lines are in the range 0.0 - 5.0 eV and equivalent width in the range 20 Å to 180 Å. We have assumed local thermodynamic equilibrium (LTE) for our calculations. A recent version of MOOG of Sneden (1973) is used. Model atmospheres (available at <http://cfaku5.cfa.harvard.edu/> and labelled with a suffix odnew) were selected from the Kurucz grid of model atmospheres with no convective over shooting. Solar abundances are taken from Asplund et al.(2005).

The microturbulent velocity is estimated at a given effective temperature by demanding that there be no dependence of the derived Fe I abundance on the equivalent width of the corresponding lines.

The effective temperature is determined by making the slope of the abundance versus excitation potential of Fe I lines to be nearly zero. The initial value of temperature is taken from the photometric estimates and arrived at a final value by an iterative method with the slope nearly equal to zero. Figures 3 and 4 show abundances of Fe I and Fe II as a function of excitation potential and equivalent width respectively.

The surface gravity is fixed at a value that gives same abundances for Fe I and Fe II lines. Derived atmospheric parameters are listed in Table 5.



**Figure 3.** The iron abundances of stars are shown for individual Fe I and Fe II lines as a function of excitation potential. The solid circles indicate Fe I lines and solid triangles indicate Fe II lines.

## 6 ABUNDANCE ANALYSIS

Elemental abundances are calculated from the measured equivalent widths of lines due to neutral and ionized elements using a recent version of MOOG of Sneden (1973) and the adopted model atmospheres. A master line list of all the elements is generated comparing the spectra of the

**Table 4A: Fe lines used for deriving atmospheric parameters for the first 6 objects**

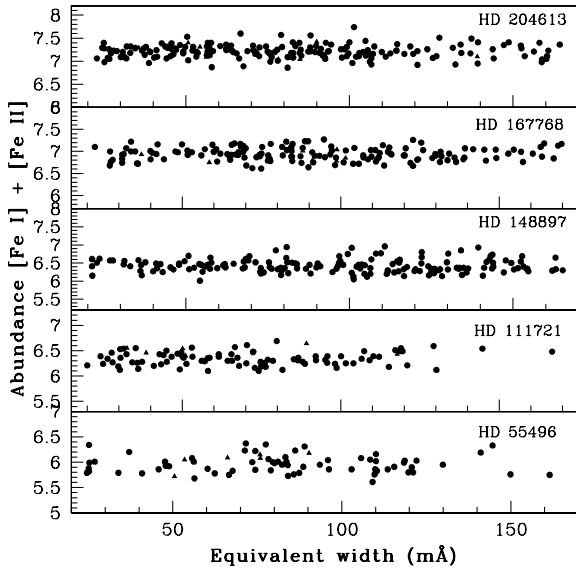
Wavelength(Å)	Element	$E_{low}(ev)$	log gf	HD 55496	HD 89668	HD 92545	HD 104979	HD 107574	HD 111721
4062.440	Fe I	2.850	-0.860	-	-	110.3	-	-	-
4114.440		2.830	-1.300	-	-	-	-	-	-
4132.900		2.850	-1.010	-	-	-	-	-	-
4143.870		1.560	-0.510	-	-	-	-	-	-
4147.670		1.490	-2.100	-	-	-	-	-	-
4153.900		3.400	-0.320	-	-	-	-	-	-
4154.500		2.830	-0.690	-	-	-	-	-	-
4184.890		2.830	-0.870	-	-	151.2	143.1	-	-

This table is available in its entirety in online only. A portion is shown here for guidance regarding its form and content.

**Table 4B: Fe lines used for deriving atmospheric parameters for the next 6 objects**

Wavelength(Å)	Element	$E_{low}(ev)$	log gf	HD 122202	HD 126681	HD 148897	HD 164922	HD 167768	HD 204613
4062.440	Fe I	2.850	-0.860	-	-	-	-	-	- 102.9
4114.440		2.830	-1.300	-	-	129.8	-	-	-
4132.900		2.850	-1.010	-	-	-	-	-	107.6
4143.870		1.560	-0.51	-	-	-	-	-	-
4147.670		1.490	-2.100	-	-	-	-	-	114.6
4153.900		3.400	-0.320	-	-	-	-	-	-
4154.500		2.830	-0.690	-	-	-	-	-	-
4184.890		2.830	-0.870	-	-	-	-	-	105.0

This table is available in its entirety in online only. A portion is shown here for guidance regarding its form and content.



**Figure 4.** The iron abundances of stars are shown for individual Fe I and Fe II lines as a function of equivalent width. The solid circles indicate Fe I lines and solid triangles indicate Fe II lines.

programme stars with the spectrum of Arcturus. The presented line lists contain only those lines which are used for abundance calculation. Even though we could detect many lines for each element, only a few were usable for abundance calculation, the others being either distorted or blended with contributions from other species. The log gf values of the atomic lines are taken from literature consulting various sources, such as, Aoki et al. (2005, 2007), Goswami et al. (2006), Jonsell et al. (2006), Luck and Bond (1991), Snenen et al. (1996), and Kurucz atomic line database (Kurucz 1995a,b). The log gf values for a few La lines are taken

from Lawler et al. (2001). We have estimated abundances for many elements Na, Mg, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Zn and for heavy elements Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm, Eu and Dy. For the elements Sc, V, Mn, Ba, La and Eu, spectrum synthesis is used to find the abundances considering hyperfine structure. The line lists for each region that is synthesised are taken from Kurucz atomic line list (<http://www.cfa.harvard.edu/amdata/ampdata/kurucz23/sekur.html>). A few examples of spectrum synthesis calculations are shown in Figures 5, 6 and 7.

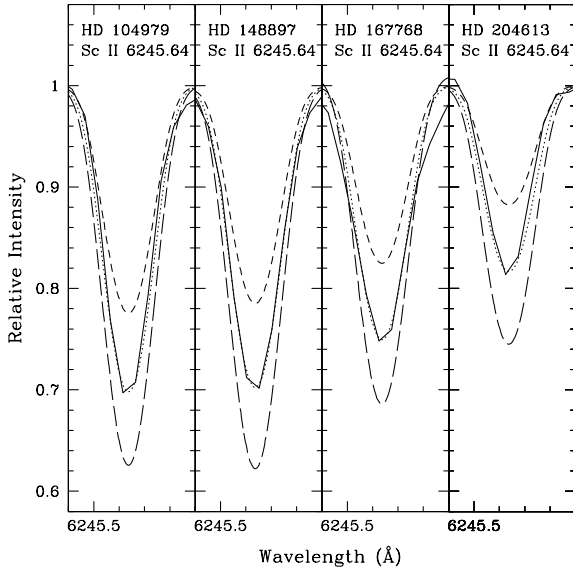
Derived abundance ratios with respect to iron are listed in Table 6. In Table 7, we have presented [ls/Fe], [hs/Fe] and [hs/ls] values, where ls represents light s-process elements Sr, Y and Zr and hs represents heavy s-process elements Ba, La, Ce, Nd and Sm. Lines used for the abundance calculation of these elements are listed in Tables 8A, 8B, 9A and 9B.

## 6.1 Carbon

We have derived the Carbon abundance for our objects whenever possible using the spectrum synthesis calculation of C I line at 5380.337 Å. The line list is generated from Kurucz atomic and molecular line database (<http://www.cfa.harvard.edu/amdata/ampdata/kurucz23/sekur.html>). This line appears heavily distorted in the spectra of stars HD 89668, HD 111721 and HD 126681 and hence C abundance could not be determined for these objects from this line. In case of HD 148897, a very weak feature of C I at 5380.337 Å is detected; however, this line could not be used for abundance determination using the spectrum synthesis calculation. For the stars HD 148897 and HD 111721 the Carbon abundance is determined using spectrum synthesis calculation of the CH band at 4300 Å. For HD 126681 we could not find C abundance due to severe line distortion and blending throughout the spectrum. Estimated [C/Fe] ratios are listed in Table 6. We have derived

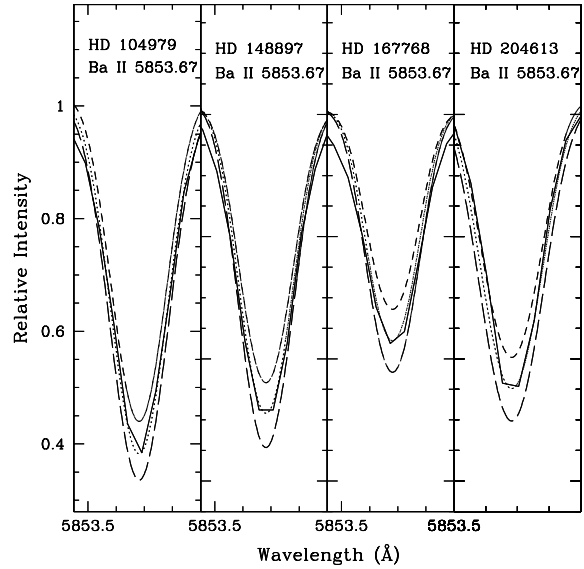
**Table 5: Derived atmospheric parameters and Carbon isotopic ratios for the programme stars**

Star Name.	$T_{eff}$ K	$\log g$	$\zeta$ km s <sup>-1</sup>	[Fe I/H]	[Fe II/H]	$C^{12}/C^{13}$
HD 55496	4850	2.05	1.52	-1.49	-1.41	4
HD 89668	5400	4.35	2.35	-0.13	-0.19	19.1
HD 92545	6380	4.65	1.45	-0.21	-0.22	-
HD 104979	5060	2.67	1.55	-0.26	-0.31	9.9
HD 107574	6250	2.9	1.35	-0.65	-0.60	-
HD 111721	5212	2.6	1.30	-1.11	-1.11	-
HD 122202	6430	4.0	2.08	-0.63	-0.65	13.2
HD 126681	5760	4.65	0.9	-0.90	-0.92	-
HD 148897	4285	0.6	1.83	-1.02	-0.99	13
HD 164922	5400	4.3	0.09	0.22	0.23	12
HD 167768	5070	2.55	1.49	-0.51	-0.56	-
HD 204613	5875	4.2	1.22	-0.24	-0.24	11.1



**Figure 5.** Spectral-synthesis fits of Sc II line at 6245.64 Å. The dotted lines indicate the synthesized spectra and the solid lines indicate the observed line profiles. Two alternative synthetic spectra for  $[X/Fe] = +0.3$  (long-dashed line) and  $[X/Fe] = -0.3$  (short-dashed line) are shown to demonstrate the sensitivity of the line strength to the abundances.

the  $^{12}C/^{13}C$  ratio for seven objects from spectrum synthesis of the CH band. The initial  $^{12}C/^{13}C$  is fixed at solar value and then varied to fit the observed spectrum for the determined Carbon abundances. The estimated values lie in the range 4 to 19 and are presented in Table 5 along with the atmospheric parameters. The line list for the synthesis of CH band is taken from the Kurucz database for molecular lines. We have derived a  $[C/H]$  value of -0.23 and -1.23 for two cyanogen weak giants HD 104979 and HD 148897. For these objects Luck (1991) reported the  $[C/H]$  values -0.38 and -0.94 respectively. We have determined a Carbon abundance of 8.68 dex for HD 204613 while Smith et al. (1993) reported 8.91 dex for the same object. North et al. (1994) has given the  $[C/H]$  ratios -0.07 and -0.03 respectively for HD 92545 and HD 107574. We have derived slightly lower  $[C/H]$  values for these objects. For HD 92545 and HD 107574 our estimated  $[C/H]$  values are -0.37 and -0.18 respec-

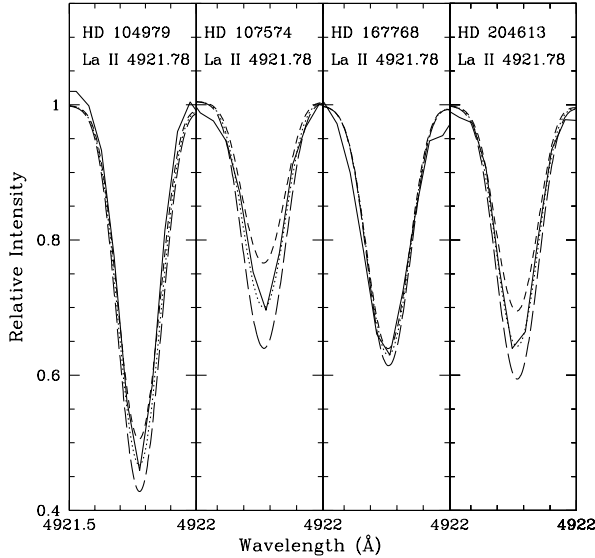


**Figure 6.** Spectral-synthesis fits of Ba II line at 5853.67 Å. The dotted lines indicate the synthesized spectra and the solid lines indicate the observed line profiles. Two alternative synthetic spectra for  $[X/Fe] = +0.3$  (long-dashed line) and  $[X/Fe] = -0.3$  (short-dashed line) are shown to demonstrate the sensitivity of the line strength to the abundances.

tively. Masseron et al. (2010) listed the  $[C/Fe]$  ratio of these two objects as 0.32 and 0.39 respectively. Carbon abundance for HD 122202 is not available in the literature. We have derived -0.13 for  $[C/H]$  and 0.5 for  $[C/Fe]$  in this object. Our estimate of  $[C/H] \sim -0.48$  and  $[C/Fe] \sim 0.03$  for HD 167768 are in good agreement with the estimate of -0.63 and -0.02 respectively of Luck and Heiter (2007).

## 6.2 Na and Al

The abundance of sodium is derived for all the objects except HD 122202. For most of the objects we have used the lines at 5682.65 and 5688.22 Å. We have also used the doublet lines at 5890.9 and 5895.9 Å for determination of sodium abundances. However the resonance lines are sensitive to non-LTE effects. The observed LTE abundance ranges between -0.29 to 0.49 in the programme stars.



**Figure 7.** Spectral-synthesis fits of La II line at 4921.78 Å. The dotted lines indicate the synthesized spectra and the solid lines indicate the observed line profiles. Two alternative synthetic spectra for  $[X/Fe] = +0.3$  (long-dashed line) and  $[X/Fe] = -0.3$  (short-dashed line) are shown to demonstrate the sensitivity of the line strength to the abundances.

Even though we could measure a few Al lines in our programme stars spectra, these are not usable for abundance determination of Al.

### 6.3 Mg, Si, Ca, Sc, Ti, V

We have measured several lines due to these elements. Except for HD 92545 and HD 104979 that show near-solar values, all other stars show mild enhancement of Mg with  $[Mg/Fe] \geq 0.15$ .  $[Mg/Fe]$  in HD 148897 with a metallicity of  $-1.02$  is  $\sim 0.63$ , slightly higher than as expected for classical enhancement of  $\alpha$ -elements in stars with  $[Fe/H] \sim -1.0$  (Goswami & Prantzos 2000). Abundance of Si could not be estimated as none of the Si lines are found usable for abundance determination. Ca shows a near solar value in HD 92545, HD 104979, HD 126681 and HD 164922. In the rest of the objects Ca is found to be mildly enhanced.

Sc abundance is determined using spectrum synthesis calculation of Sc II line at 6245.63 Å considering hyperfine structure from Prochaska and Mc William (2000). We could determine Sc abundance in seven of the programme stars. Except HD 204613 with  $[Sc/Fe]$  value 0.17 all the other objects show mild underabundance of Sc.

Mild overabundance or near-solar abundance for Ti is noticed in all the programme stars except for HD 89668 and HD 92545. More than ten good lines of Ti are used for abundance determination.

Abundance of V is estimated from spectrum synthesis calculation of V I line at 5727.028 Å taking into account the hyperfine components from Kurucz database. We could determine V abundance only in six objects. While HD 148897 shows a mild under abundance with  $[V/Fe] \approx -0.18$ , HD 89668, HD 104979, HD 167768, and HD 204613

show near-solar values. HD 164922 shows a mild overabundance with  $[V/Fe] = 0.40$ . We have detected more than 16 V I lines but only one or two are usable for the determination of abundance; other lines appear either blended or distorted in the spectra.

### 6.4 Cr, Co, Mn, Ni, Zn

HD 122202, HD 107574, HD 148897 and HD 164922 show a near-solar abundance for Cr. The rest of the stars in our sample are mildly underabundant in Cr. HD 55496 however shows a larger underabundance with  $[Cr/Fe] = -0.35$ . Cr abundances measured using Cr II lines whenever possible also show similar trends.

Mn abundance is obtained using spectrum synthesis calculation of 6013.51 Å line taking into account the hyperfine structures from Prochaska & McWilliam (2000). Except for HD 89668 and HD 164922, that show a mild overabundance with  $[Mn/Fe] \sim 0.34$  and 0.14 respectively, the rest of the objects show underabundance with  $[Mn/Fe] \leq -0.23$ .

Except HD 92545 with  $[Co/Fe] \sim 0.80$ , all other stars in our sample show near-solar values or mild underabundance for Co.

Abundances of Ni measured from Ni I lines give near-solar values for all the stars.

HD 122202 is mildly overabundant in Zn with  $[Zn/Fe] \sim 0.59$ . The rest of the objects show near-solar values.

### 6.5 Sr, Y, Zr

The abundance of Sr is estimated in seven stars using Sr I line at 4607.327 Å. Sr is overabundant in HD 89668 and HD 204613 with  $[Sr/Fe] > 1.0$ . The other five objects HD 55496, HD 104979, HD 148897, HD 164922 and HD 167768 give  $[Sr/Fe]$  ratios in the range 0.30 and 0.99. Abundance of Sr could not be estimated in the remaining objects as the line at 4607.327 Å appears distorted in their spectra. None of the Sr II lines detected are found suitable for abundance estimate of Sr.

The abundance of Y is measured in all the stars. Y is overabundant in HD 122202 and HD 107574 with  $[Y/Fe]$  ratio  $\geq 1.0$ . HD 204613 and HD 55496 show  $[Y/Fe]$  values of 0.97 and 0.85 respectively. The remaining stars show near-solar values or mild overabundance.

We could derive Zr abundance for five stars. HD 204613 and HD 104979 show overabundance with  $[Zr/Fe]$  values 1.14 and 0.85 respectively. The rest show mild enhancement with  $[Zr/Fe] \geq 0.2$ .

### 6.6 Ba, La, Ce, Pr, Nd, Sm, Eu, Dy

As many lines due to Ce, Pr, Nd, Sm and Dy could be measured on our spectra the standard abundance determination method using equivalent width measurements are used for abundance estimates. Spectrum synthesis calculation is also performed for Ba, La and Eu. We have estimated the abundance for Ba and Ce in all the stars.

Barium (Ba): We have determined Ba abundance from spectrum synthesis calculation using Ba II line at 5853.668 Å considering hyperfine components from McWilliam (1998). Four stars in our sample HD 92545, HD 104979, HD 107574

and HD 204613 show overabundance with  $[\text{Ba}/\text{Fe}] \geq 0.9$ . HD 122202, HD 55496 and HD 126681 show only a mild overabundance. Four objects HD 89668, HD 111721, HD 148897, and HD 167768 show underabundance with  $[\text{Ba}/\text{Fe}]$  in the range  $-0.09$  to  $-0.65$  (Table 11).

**Lanthanum (La):** We have derived La abundance for all the programme stars except for HD 55496 and HD 126681 from spectrum synthesis calculation of La II line at 4921.77 Å considering hyperfine components from Jonsell et al. (2006). Except for HD 111721, HD 148897, HD 164922 and HD 167768, La in all other stars are found to be overabundant with  $[\text{La}/\text{Fe}] \geq 0.9$ . HD 111721, HD 148897, HD 164922 and HD 167768 show  $[\text{La}/\text{Fe}]$  of 0.31, 0.29, 0.15 and  $-0.54$  respectively.

**Cerium (Ce):** We have derived Ce abundance for all the programme stars. Six of the programme stars, HD 89668, HD 92545, HD 104979, HD 111721, HD 122202 and HD 204613 show overabundance with  $[\text{Ce}/\text{Fe}] \geq 1.0$ . Estimated  $[\text{Ce}/\text{Fe}]$  for HD 107574 is  $\sim 0.6$ . While two stars HD 55496 and HD 167768 show almost near-solar values for  $[\text{Ce}/\text{Fe}]$ , HD 148897 and HD 164922 show mild underabundance with  $[\text{Ce}/\text{Fe}] \approx -0.10$ .

**Praseodymium (Pr):** We could derive Pr abundance for five programme stars mainly using the Pr II line at 5292.619 Å. A mild over enhancement of Pr is seen in HD 55496 with  $[\text{Pr}/\text{Fe}] \sim 0.43$ ; the rest show overabundance with  $[\text{Pr}/\text{Fe}] \geq 1.0$ .

**Neodymium (Nd):** Abundance of Nd is estimated for seven programme stars. Two stars HD 148897 and HD 167768 give  $[\text{Nd}/\text{Fe}]$  values  $\sim 0.13$  and  $0.65$  respectively. HD 111721 shows a large overabundance with  $[\text{Nd}/\text{Fe}] \sim 2.1$ . All other stars show overabundance with  $[\text{Nd}/\text{Fe}] \geq 1.0$ .

**Samarium (Sm):** HD 148897 shows a mild overabundance with  $[\text{Sm}/\text{Fe}] \sim 0.58$ . HD 89668, HD 104979, HD 122202, HD 126681 and HD 204613 show overabundance with  $[\text{Sm}/\text{Fe}] \geq 1.0$ . Estimated  $[\text{Sm}/\text{Fe}]$  in HD 167768 is  $\sim 0.90$ .

**Europium (Eu):** We could determine Eu abundance in four of the programme stars using spectrum synthesis of Eu II lines at 6645.130 Å by considering the hyperfine components from Worley et al. (2013). Eu shows mild overabundance in HD 89668, HD 92545 and HD 167768 with  $[\text{Eu}/\text{Fe}] \sim 0.38, 0.40$  and  $0.26$  respectively. HD 204613 shows a near-solar value with  $[\text{Eu}/\text{Fe}] \sim 0.06$ .

**Dysprosium (Dy):** We could derive Dy abundance for three objects HD 148897, HD 167768 and HD 204613 using Dy II lines at 4103.310 Å and 4923.167 Å. HD 167768 and HD 204613 show overabundance with  $[\text{Dy}/\text{Fe}] \geq 1.0$ . HD 148897 shows a near-solar value of  $\sim 0.02$ .

## 7 DISCUSSION ON INDIVIDUAL STARS

**HD 55496:** Bond (1974) has classified this high velocity object as a sub-giant CH star. MacConnell (1972) included this in the category of weak lined metal-deficient Ba II star. Being a high velocity object with lower metallicity, ( $[\text{Fe}/\text{H}] = -1.45$ ) HD 55496 seems to show the extreme halo kinematics. Luck and Bond (1991) has studied this object and reported abundances for a few elements (Table 11). Estimated Ba abundance ( $[\text{Ba}/\text{Fe}] = 0.57$ ) does not qualify the object to be a typical CH star. Light s-process elements Sr,

Y and Zr are more abundant in this star than the heavy s-process elements Ba, Ce, and Pr.

**HD 89668:** We present first time detailed abundances for this object. This object shows large enhancements in La, Ce, Pr, Nd and Sm with  $[\text{X}/\text{Fe}]$  values  $\geq 1$ ; however, Ba is slightly underabundant with  $[\text{Ba}/\text{Fe}] \sim -0.24$ .

**HD 92545, HD 107574:** North and Duquennoy (1991) have categorized these objects as F str Lambda 4077 stars following the classification of Bidelman (1981). Allen and Barbuy (2006a, 2006b) have reported detailed chemical abundances for these objects (Table 11). For HD 92545, our Ce abundance is higher than their estimates. Other elements show a close similarity and within the error limits. For HD 107574, our results are fairly in good agreement with their estimates.

**HD 104979, HD 148897:** Luck (1991), identified these objects as cyanogen weak giants and reported elemental abundances for Y, Zr, Ce, Nd and Eu. Our results closely match with their values. In addition to these elements we could measure abundances for Sr, Ba, La, Sm, Pr and Dy. Similar to the two cyanogen weak giants HD 188650 and HD 214714 from our paper I, the object HD 148897 also does not show large enhancement in heavy elements. These three objects are of the same spectral type. The object HD 104979 shows enhancements in Ba with  $[\text{Ba}/\text{Fe}] = 0.94$ . Estimated metallicities of these objects are in the range  $-0.2$  to  $-1.2$ .

**HD 111721:** Gratton and Sneden (1994) have studied this object and reported abundances for heavy elements. From our analysis and also from Gratton and Sneden (1994) this object does not show enhancement in heavy elements. The metallicity of this object is  $= -1.11$ . This object could be a possible member of the group of CEMP-no stars of Beers and Christlieb's (2005) carbon star classification scheme.

**HD 122202, HD 204613:** These two objects are CH sub-giants. Luck and Bond (1991) have studied the object HD 122202 and reported abundances for a few s-process elements. HD 204613 was studied by Smith (1984); these authors gave the abundances for Y, Zr, Ba and Nd in this object. In addition to these elements we estimated the abundances for Sr, La, Ce, Pr, Sm, Eu and Dy in HD 204613 and La, Pr and Sm in HD 122202. The object HD 122202 shows a large enhancement in Ce, Pr and Nd. However, Ba is only mildly enhanced with  $[\text{Ba}/\text{Fe}] \sim 0.33$ . HD 204613 shows a large enhancement in all the elements except Eu. According to Beers and Christlieb (2005) classification, this object fall in to the group of CEMP-s stars with  $[\text{Ba}/\text{Fe}] \sim 1.04$  and  $[\text{Ba}/\text{Eu}] \sim 0.98$ . McClure (1997) have confirmed these objects as binaries. Information on radial velocity variability and orbital elements for these objects are available in McClure (1997). While HD 122202 shows radial velocity variations in the range  $-14.81$  to  $-7.64$  with an orbital period of  $1290 \pm 9$  days; HD 204613 exhibits radial velocity variations from  $-95.07$  to  $-87.85$  with period  $878 \pm 4$  days.

**HD 126681:** We have presented the first time abundance estimates for the elements Ce, Nd and Sm in this object. Fulbright (2000) has studied this object and reported abundances for Y and Ba. This object shows a large enhancement in Nd and Sm but other heavy elements are only mildly enhanced.

**HD 164922:** The object HD 164922 is listed as a CH star by many authors, however, this object does not seem



Table 6: Elemental abundances

Star Name	[C/Fe]	[Na I/Fe]	[Mg I/Fe]	[Ca I/Fe]	[Sc II/Fe]	[Ti I/Fe]	[Ti II/Fe]	[V I/Fe]	[Cr I/Fe]	[Cr II/Fe]	[Mn I/Fe]	[Co I/Fe]	[Ni I/Fe]	[Zn I/Fe]
Sub giant														
CH stars														
HD 122202	0.50	-	0.32	0.33	-	-	0.36	-	0.11	-	-	-	0.14	0.59
HD 204613	0.49	0.08	0.11	0.13	0.17	0.26	0.41	-0.01	-0.06	0.08	-0.33	-0.19	0.04	-
#CH stars														
*HD 55496	1.01	0.4	0.33	0.46	-	-0.1	-0.16	0.19	-0.35	-0.21	-	-	-0.18	0.02
HD 89668	0.05	0.08	0.28	0.63	0.0	-0.26	-0.38	-	-0.09	-0.27	0.34	-0.23	-0.12	-
HD 92545	0.68	0.01	-0.09	-0.05	-	0.03	0.6	-	-0.15	-	-	0.8	0.01	-
HD 104979	0.03	-0.01	0.07	0.05	-0.01	0.14	0.32	0.05	-0.02	0.06	-0.23	0.28	0.04	-0.03
HD 107574	0.47	0.49	-	0.19	-0.13	0.32	0.34	-	0.1	-0.26	-	-	0.01	-
HD 111721	0.08	0.07	0.46	0.41	-	0.46	0.03	-	-0.21	-0.31	-	-	-0.07	-
HD 126681	-	-0.26	0.44	0.07	-	0.52	0.60	-	0.1	-	-	-	-0.08	-
HD 148897	-0.21	-0.29	0.63	0.19	-0.33	0.11	0.46	-0.18	-0.22	0.0	-0.54	0.06	-0.13	-0.26
HD 164922	-0.15	-0.02	0.36	-0.07	-0.47	0.25	0.05	0.40	0.04	0.06	0.14	0.13	0.06	0.19
HD 167768	0.03	0.04	0.17	0.22	-0.04	0.17	0.41	0.2	-0.09	-0.21	-0.56	-0.03	-0.09	0.18

# Objects from the CH star catalogue of Bartkevicius (1996)

\* Objects are also included in Ba star catalogue of Lü (1991)

Table 6: continued

Star Name	[Sr I/Fe]	[Y II/Fe]	[Zr II/Fe]	[Ba II/Fe]	[La II/Fe]	[Ce II/Fe]	[Pr II/Fe]	[Nd II/Fe]	[Sm II/Fe]	[Eu II/Fe]	[Dy II/Fe]
Sub giant											
CH stars											
HD 122202	-	1.44	-	0.33	0.9	1.62	1.26	-	1.77	-	-
HD 204613	1.71	0.97	1.14	1.04	1.21	1.24	1.52	1.02	1.61	0.06	1.77
#CH stars											
*HD 55496	0.82	0.85	0.52	0.57	-	0.13	0.43	-	-	-	-
HD 89668	1.06	0.55	-	-0.24	1.87	1.52	1.66	1.44	1.23	0.38	-
HD 92545	-	0.23	-	0.91	0.95	1.6	-	-	-	-	-
HD 104979	0.99	0.71	0.85	0.94	1.11	1.06	1.04	1.13	1.17	0.40	-
HD 107574	-	1.02	-	0.97	1.04	0.6	-	-	-	-	-
HD 111721	-	0.05	-	-0.09	0.31	1.6	-	2.1	-	-	-
HD 126681	-	0.02	-	0.27	-	0.67	-	1.2	1.07	-	-
HD 148897	0.31	0.03	-0.47	-0.65	0.29	-0.16	-	0.13	0.58	-	0.02
HD 164922	0.79	0.14	-	0.28	0.15	-0.09	-	-	-	-	-
HD 167768	0.77	0.56	0.2	-0.36	-0.54	0.06	-	0.65	0.9	0.26	1.04

# Objects from the CH star catalogue of Bartkevicius (1996)

\* Objects are also included in Ba star catalogue of Lü (1991)

Table 7: Observed values for [Fe/H], [ls/Fe], [hs/Fe] and [hs/ls]

Star Name	[Fe/H]	[ls/Fe]	[hs/Fe]	[hs/ls]	Remarks
HD 55496	-1.49	0.73	0.38	-0.35	1
HD 89668	-0.13	0.81	1.16	0.35	1
HD 92545	-0.21	0.23	1.15	0.92	1
HD 104979	-0.26	0.85	1.03	0.18	1
HD 104979	-0.47	0.6	1.0	0.4	2
HD 107574	-0.48	1.02	0.87	-0.15	1
HD 111721	-1.11	0.05	0.98	0.93	1
HD 122202	-0.63	1.44	1.16	-0.28	1
HD 126681	-0.90	0.02	0.80	0.78	1
HD 148897	-1.02	-0.13	0.01	0.14	1
HD 164922	0.22	0.47	0.10	-0.37	1
HD 167768	-0.51	0.51	0.14	-0.37	1
HD 204613	-0.24	1.27	1.16	-0.11	1
HD 204613	-0.35	1.0	0.6	-0.4	2

1. Our work; 2: Busso et al. (2001)

Table 8A: Equivalent widths in mÅ of lines used for the calculation of light element abundances for first 6 objects

Wavelength(Å)	Element	$E_{low}(ev)$	log gf	HD 55496	HD 89668	HD 92545	HD 104979	HD 107574	HD 111721
5682.650	Na I	2.100	-0.700	58.07	208.7	63.7	115.9	50.1	-
5688.220		2.100	-0.400	-	205.3	89.9	131.6	-	29.9
5889.950		0.000	0.100	275.5	-	-	450.2	253.8	263.3
5895.920		0.000	-0.200	-	-	225.4	379.5	226.1	245.6
4702.990	Mg I	4.350	-0.666	103.2	-	172.8	188.9	-	143.1
6318.720		5.108	-1.730	15.88	86.1	82.6	137.4	-	79.4
5528.000		4.350	-0.490	142.3	-	162.6	202.4	-	139.0
4098.500	Ca I	2.525	-0.540	-	-	-	-	-	-

This table is available in its entirety in online only. A portion is shown here for guidance regarding its form and content.

**Table 8B: Equivalent widths in mÅ of lines used for the calculation of light element abundances for next 6 objects**

Wavelength(Å)	Element	$E_{low}(ev)$	log gf	HD 122202	HD 126681	HD 148897	HD 164922	HD 167768	HD 204613
5682.650	Na I	2.100	-0.700	-	22.8	73.7	137.6	93.2	87.5
5688.220		2.100	-0.400	-	-	93.0	143.4	118.7	106.2
5889.950		0.000	0.100	-	263.2	396.5	-	379.1	377.3
5895.920		0.000	-0.200	-	234.5	340.2	601.4	329.7	-
4702.990	Mg I	4.350	-0.666	147.3	-	186.2	334.3	182.4	232.6
6318.720		5.108	-1.730	-	60.7	35.3	133.2	35.5	88.3
5528.000	Ca I	4.350	-0.490	-	156.7	212.2	320	205.3	201.8
4098.500		2.525	-0.540	-	-	-	130.6	-	79.2

This table is available in its entirety in online only. A portion is shown here for guidance regarding its form and content.

**Table 9A: Equivalent widths in mÅ of lines used for abundance determination of heavy elements for the first 6 objects**

Wavelength(Å)	Element	$E_{low}(ev)$	log gf	HD 55496	HD 89668	HD 92545	HD 104979	HD 107574	HD 111721
4607.327	Sr I	0.000	-0.570	36.42	140.9	-	91.55	-	-
4854.863	Y II	0.992	-0.380	-	90.5	57.6	120.6	-	-
4883.685		1.084	0.070	-	74.4	89.9	121.2	106.8	51.7
5087.416		1.080	-0.170	103.5	-	72.1	91.82	-	56.2
5119.112		0.992	-1.360	41.16	-	27.4	55.28	-	-
5205.724		1.033	-0.340	42.89	-	-	-	-	-
5289.815		1.033	-1.850	27.11	-	-	33.81	-	-
5544.611		1.738	-1.090	-	-	-	36.53	-	-

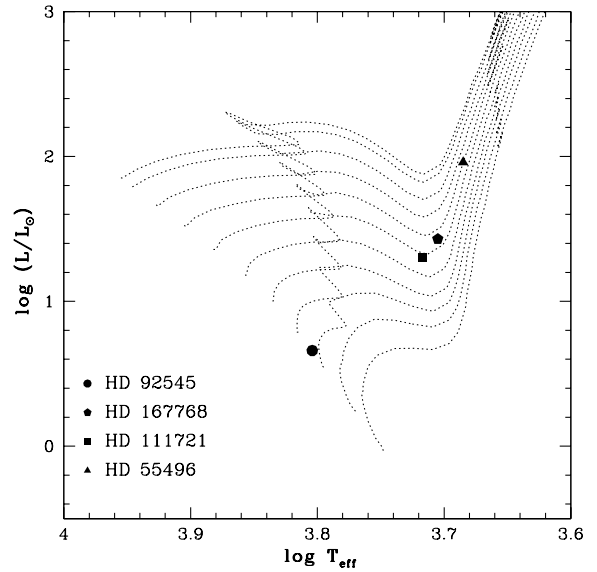
This table is available in its entirety in online only. A portion is shown here for guidance regarding its form and content.

to show any characteristics of CH stars. Mishenina et al. (2013) have studied this object and reported abundances for a few heavy elements that show almost near-solar values for Zr, Ba, Ce, Nd, Sm and Eu. Our estimated Ba and Ce abundances give  $[Ba/Fe] \sim 0.28$  and  $[Ce/Fe] \sim -0.09$  for this object.

**HD 167768:** Luck and Heiter (2007) has studied this object and reported abundances for Y, Ba, Ce, Pr, Nd, Eu. Along with these elements we have estimated abundances for Sr, Zr, La and Sm. This object does not show large enhancement of heavy elements, a characteristic of CH stars.

## 8 STELLAR MASSES

We could estimate the stellar masses for eight objects in our sample from their locations in the Hertzsprung-Russel diagram (Figures 8 and 9), using the evolutionary tracks (Girardi et al. 2000) in the mass range of  $0.15 M_{\odot}$  to  $7.0 M_{\odot}$  and the Z values from 0.0004 to 0.03. These evolutionary tracks are available at <http://pleiadi.pd.astro.it/>. For the objects with near-solar metallicity we have selected an initial composition of  $Z=0.0198$ ,  $Y=0.273$ . The masses derived using spectroscopic temperature estimates are presented in Table 12. For six stars in our sample that have metallicities  $< -0.5$  we used the evolutionary tracks corresponding to  $Z = 0.008$ . It is to be noted that the values of the masses obtained for these objects with  $Z = 0.008$  are found to be similar to those obtained using evolutionary tracks corresponding to  $Z = 0.019$ . Derived stellar masses are in the range  $0.6 M_{\odot}$  to  $1.6 M_{\odot}$  with HD 55496 having a mass of  $1.6 M_{\odot}$  and HD 148897  $\sim 0.6 M_{\odot}$ . Stellar masses could not be estimated for the rest of the objects as the parallax estimates are not available in the literature.



**Figure 8.** The location of HD 92545, HD 167768, HD 111721 and HD 55496 are indicated in the H-R diagram. The masses are derived using the evolutionary tracks of Girardi et al. (2000). The evolutionary tracks for masses 1, 1.1, 1.2, 1.3 1.4, 1.5, 1.6 1.7, 1.8, 1.9 and  $1.95 M_{\odot}$  from bottom to top are shown in the Figure.

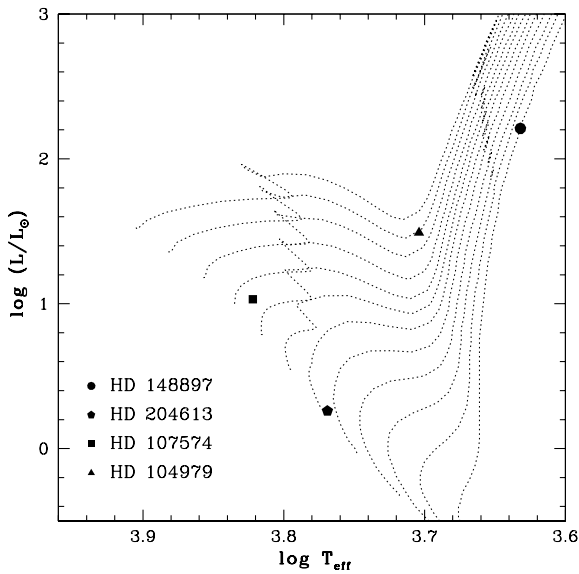
## 9 PARAMETRIC MODEL BASED STUDY

Elements heavier than iron are mainly produced by two neutron-capture processes, the s-process and the r-process. Observed abundances of heavy elements estimated using model atmospheres and spectral synthesis techniques do not provide direct quantitative estimates of the relative contributions from s- and/or r- process nucleosynthesis. Identification of the dominant processes contributing to the heavy

**Table 9B: Equivalent widths in mÅ of lines used for abundance determination of heavy elements for the next 6 objects**

Wavelength(Å)	Element	$E_{low}(ev)$	log gf	HD 122202	HD 126681	HD 148897	HD 164922	HD 167768	HD 204613
4607.327	Sr I	0.000	-0.570	-	-	89.9	58.5	68.6	77.31
4854.863	Y II	0.992	-0.380	-	-	98.6	53.8	72.2	82.63
4883.685		1.084	0.070	129.5	28.6	114.5	-	80.6	101.4
5087.416		1.080	-0.170	-	23.8	82.3	40.5	66.1	86.53
5119.112		0.992	-1.360	-	-	41.6	19.0	16.2	47.09
5205.724		1.033	-0.340	-	-	-	-	-	92.26
5289.815		1.033	-1.850	-	-	-	-	14.2	15.22
5544.611		1.738	-1.090	-	-	18.6	-	11.7	29.54

This table is available in its entirety in online only. A portion is shown here for guidance regarding its form and content.



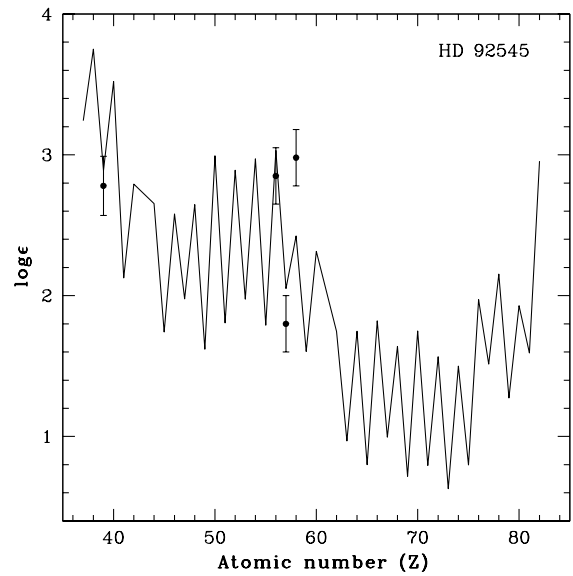
**Figure 9.** The location of HD 148897, HD 204613, HD 107574 and HD 104979 are indicated in the H-R diagram. The masses are derived using the evolutionary tracks of Girardi et al. (2000). The evolutionary tracks are shown for masses 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9 and 1.95  $M_{\odot}$  from bottom to top.

element abundances in the stars is likely to provide clues to their origin. We have investigated ways to delineate the observed abundances into their respective r- and s-process contributions in the framework of a parametric model using an appropriate model function. The origin of the n-capture elements is explored by comparing the observed abundances with predicted s- and r- process contributions following Goswami et al. (2010c, and references there in). The  $i$ th element abundance can be calculated as

$$N_i(Z) = A_s N_{is} + A_r N_{ir} 10^{[Fe/H]}$$

where  $Z$  is the metallicity of the star,  $N_{is}$  indicates the abundance from s-process in AGB star,  $N_{ir}$  indicates the abundance from r-process;  $A_s$  indicates the component coefficient that correspond to contributions from the s-process and  $A_r$  indicates the component coefficient that correspond to contributions from the r-process.

We have utilized the solar system s- and r-process isotopic abundances from stellar models of Arlandini et al. (1999). The observed elemental abundances are scaled to the metallicity of the corresponding CH star and are normalised to their respective Ba abundances. Elemental abun-



**Figure 10.** Solid curve represent the best fit for the parametric model function  $\log \epsilon = A_s N_{si} + A_r N_{ri}$ , where  $N_{si}$  and  $N_{ri}$  represent the abundances due to s- and r-process respectively (Arlandini et al (1999), Stellar model, scaled to the metallicity of the star). The points with error bars indicate the observed abundances in HD 92545.

dances are then fitted with the parametric model function. The best fit coefficients and reduced chi-square values for a set of CH stars are given in Table 13. The best fits obtained with the parametric model function  $\log \epsilon_i = A_s N_{is} + A_r N_{ir}$  for HD 92545, HD 104979, HD 107574 and HD 204613 are shown in Figures 10 -13. The errors in the derived abundances play an important role in deciding the goodness of fit of the parametric model functions. From the parametric model based analysis we find the objects HD 92545, HD 104979, HD 107574 and HD 204613 to belong to the group of CEMP-s stars.

## 10 CONCLUSION

Results from our analyses of a group of twelve stars from the CH star catalogue of Bartkevicius (1996) are presented. Abundances for 22 elements are estimated. Except for HD 55496 with radial velocity 315.2  $\text{Kms}^{-1}$ , the rest are low velocity objects. HD 55496 is also listed in the Ba star catalogue of Lü (1991). This object with a metallicity of

**Table 10. Atmospheric parameters from literature**

Star name	Vmag	$T_{eff}$ (K)	log g	[Fe/H]	Reference
HD 55496	8.40	4850	2.05	-1.45	1
		4858	2.05	-1.48	2
		4935	2.33	-1.44	3
		4800	2.8	-1.55	4
HD 89968	9.41	5400	4.35	-0.13	1
		4811	4.45	-0.11	5
HD 92545	8.56	6380	4.65	-0.21	1
		6240	4.23	-0.26	6
HD 104979	4.13	5060	2.67	-0.26	1
		4842	2.9	-0.51	7
		4996	2.86	-0.33	8
		4825	2.34	-0.33	9
		4870	3.23	-0.51	10
		4893	2.6	-0.29	11
		4990	2.65	-0.11	12
		5250	3.25	-0.29	13
		6250	2.9	-0.65	1
		6340	3.87	-0.36	6
HD 111721	7.97	5212	2.6	-1.11	1
		5120	2.90	-1.27	3
		4995	2.52	-1.26	14
		4825	2.2	-1.54	15
		4800	3.00	-1.68	16
		5164	3.27	-0.98	17
		4940	2.40	-1.34	18
		5103	3.06	-1.22	19
		5000		-1.34	20
		5103	2.87	-1.25	21
HD 122202	9.37	6430	4.0	-0.63	1
		6600	3.0	-0.09	4
HD 126681	9.32	5760	4.65	-0.90	1
		5507	4.45	-1.17	22
		5561	4.71	-1.14	5
		5577	4.25	-1.12	2
		5475	4.65	-1.38	23
		5533	4.28	-1.14	24
		5450	4.5	-1.25	15
		5595	4.43	-1.12	22
		5625	4.95	-1.09	17
		5500	4.63	-1.45	25
HD 148897	5.25	4285	0.6	-1.02	1
		4293	1.01	-1.11	2
		4100	0.09	-1.16	4
		4345	1.5	-0.62	26
HD 167768	6.00	5070	2.55	-0.51	1
		4953	2.29	-0.69	2
		5102	2.76	-0.61	8
HD 204613	8.21	5875	4.2	-0.24	1
		5718	3.88	-0.38	2
		5650	3.80	-0.35	27
		5650	3.80	-0.35	28
		5600	3.5	-0.70	29
		5600	3.5	-0.65	30
		5663	3.75	-0.54	31

**References.**1. Our work 2. Prugniel et al. 2011, 3. Koleva & Vazdekis 2012, 4. Luck & Bond 1991, 5. Sousa et al. 2011, 6. North et al. 1994 , 7. Massarotti et al. 2008, 8. Luck & Heiter 2007, 9. Luck 1991, 10. McWilliam 1990, 11. Tomkin & Lambert 1986, 12. Sneden et al. 1981, 13. Lambert & Ries 1981, 14. Gratton et al. 2000, 15. Fulbright 2000, 16. Cavallo et al. 1997, 17. Gratton et al. 1996, 18. Ryan & Lambert 1995, 19. Gratton & Sneden 1994, 20. Pilachowski et al. 1993, 21. Gratton & Sneden 1991, 22. Nissen & Schuster 2011, 23. Sozzetti et al.2009, 24. Nissen et al. 2000, 25. Tomkin et al. 1992, 26. Kyrolainen et al. 1986, 27. Frasca et al. 2009, 28. Smith et al. 1993, 29. Rebolo et al. 1988, 30. Abia et al. 1988, 31. Smith & Lambert 1986.

Table 11: Comparison of our results with literature values

Star Name	[Sr I/Fe]	[Y II/Fe]	[Zr II/Fe]	[Ba II/Fe]	[La II/Fe]	[Ce II/Fe]	[Pr II/Fe]	[Nd II/Fe]	[Sm II/Fe]	[Eu II/Fe]	[Dy II/Fe]	References
Sub giant-CH stars												
HD 122202	-	1.44	-	0.33	0.9	1.62	1.26	-	1.77	-	-	1
	-	0.74	0.15	-	0.79	0.74	-	0.75	0.44	-	-	2
HD 204613	1.71	0.97	1.14	1.04	1.21	1.24	1.52	1.02	1.61	0.06	1.77	1
	-	1.22	1.00	0.71	-	-	-	0.77	-	-	-	3
#CH stars												
HD 55496	0.82	0.85	0.52	0.57	-	0.13	0.43	-	-	-	-	1
	-	-	0.72	-	0.52	0.32	-	0.52	0.33	-	-	2
HD 89968	1.06	0.55	-	-0.24	1.87	1.52	1.66	1.44	1.23	0.38	-	1
HD 92545	-	0.23	-	0.91	0.95	1.6	-	-	-	-	-	1
	0.67	0.64	0.75	1.04	0.72	0.60	0.44	0.42	0.24	0.32	0.09	4
HD 104979	0.99	0.71	0.85	0.94	1.11	1.06	1.04	1.13	1.17	0.40	-	1
	-	0.52	0.40	-	-	0.48	-	0.82	0.51	0.61	-	5
HD 107574	-	1.02	-	0.97	1.04	0.6	-	-	-	-	-	1
	0.67	0.64	0.75	1.04	0.72	0.6	0.44	0.42	0.24	0.14	0.09	4
HD 111721	-	0.05	-	-0.09	0.31	1.6	-	2.1	-	-	-	1
	-0.13	0.14	-0.45	0.08	0.04	0.03	0.28	0.17	0.22	0.36	-	6
	-	0.02	-	0.27	-	0.67	-	1.2	1.07	-	-	1
HD 126681	-	0.23	-	0.14	-	-	-	-	-	-	-	7
HD 148897	0.31	0.03	-0.47	-0.65	0.29	-0.16	-	0.13	0.58	-	0.02	1
	-	0.04	-0.29	-	-	0.07	-	0.01	-	-0.13	-	5
HD 164922	0.79	0.14	-	0.28	-	-0.09	-	-	-	-	-	1
	-	-0.15	0.04	-0.10	-	0.08	-	0.03	0.01	0.10	-	
HD 167768	0.77	0.56	0.2	-0.36	-0.54	0.06	-	0.65	0.9	0.26	1.04	1
	-	0.03	-	-0.03	-	-0.04	-0.10	-0.14	-	0.45	-	8

# Objects from the CH star catalogue of Bartkevicius (1996)

\* Objects are also included in Ba star catalogue of Lü (1991)

1. Our work 2. Luck & Bond (1991) 3. Smith et al. (1993) 4. Allen and Barbay (2006a) 5. Luck 1991 6. Gratton & Snenen (1994) 7. Fulbright (2000) 8. Luck & Heiter (2007)

Table 12: Stellar Masses

Star Name.	$M_v$	$\log(L/L_\odot)$	$Mass(M_\odot)$
HD 55496	-0.16	1.96	1.6
HD 92545	3.1	0.66	1.2
HD 104979	0.63	1.49	1.6
HD 107574	2.1	1.03	1.45
HD 111721	1.2	1.3	1.5
HD 148897	2.3	2.21	0.60
HD 167768	2.1	1.43	1.55
HD 204613	3.9	0.26	1.1

-

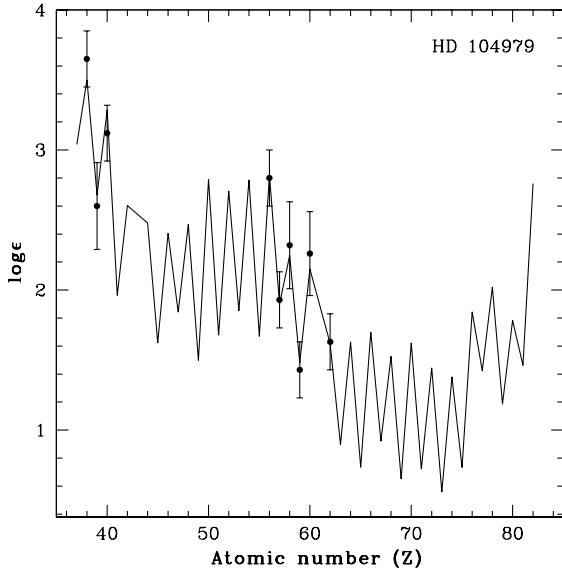


Figure 11. Solid curve represent the best fit for the parametric model function  $\log \epsilon = A_s N_{si} + A_r N_{ri}$ , where  $N_{si}$  and  $N_{ri}$  represent the abundances due to s- and r-process respectively (Arlandini et al (1999), Stellar model, scaled to the metallicity of the star). The points with error bars indicate the observed abundances in HD 104979.

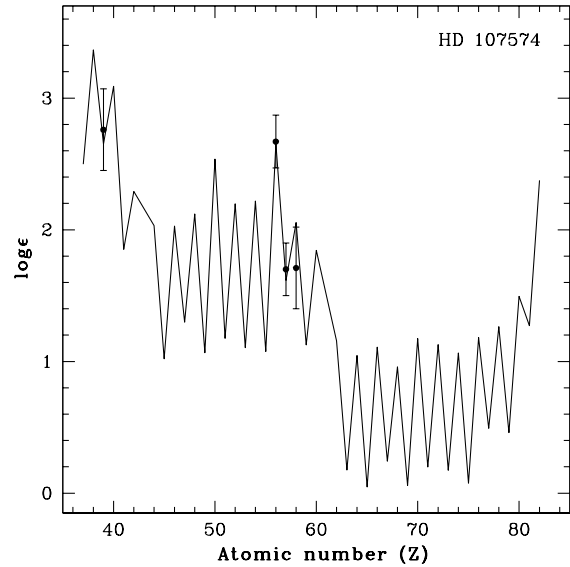
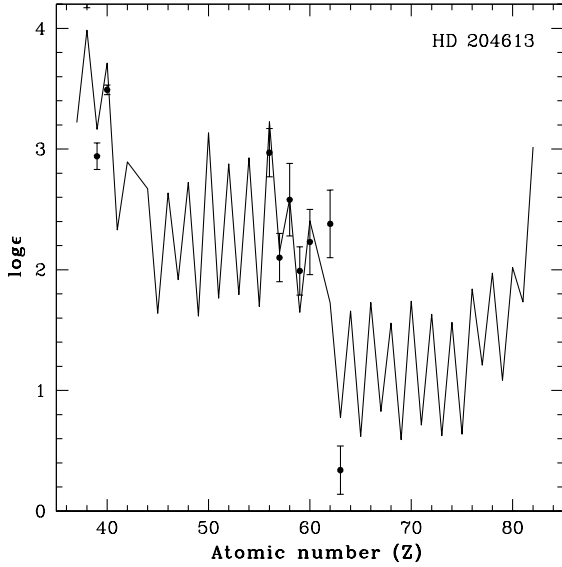


Figure 12. Solid curve represent the best fit for the parametric model function  $\log \epsilon = A_s N_{si} + A_r N_{ri}$ , where  $N_{si}$  and  $N_{ri}$  represent the abundances due to s- and r-process respectively (Arlandini et al (1999), Stellar model, scaled to the metallicity of the star). The points with error bars indicate the observed abundances in HD 107574.

**Table 13: Best fit coefficients and reduced chi-square values**

Star Name	$A_s$	$A_r$	$\chi^2$
HD 92545	$0.560 \pm 0.33$	$0.503 \pm 0.33$	2.15
HD 104979	$0.514 \pm 0.16$	$0.493 \pm 0.15$	0.50
HD 107574	$0.823 \pm 0.01$	$0.171 \pm 0.01$	1.22
HD 204613	$0.739 \pm 0.08$	$0.291 \pm 0.08$	1.65



**Figure 13.** Solid curve represent the best fit for the parametric model function  $\log \epsilon = A_s N_{si} + A_r N_{r,i}$ , where  $N_{si}$  and  $N_{r,i}$  represent the abundances due to s- and r-process respectively (Arlandini et al (1999), Stellar model, scaled to the metallicity of the star). The points with error bars indicate the observed abundances in HD 204613.

−1.49 and  $[C/Fe]$  ratio of 1.01 shows a mild enhancement in neutron-capture elements. Estimated  $[Ba/Fe]$  for this object is  $\sim 0.57$ .

In the sample we have two confirmed binaries; HD 122202 and HD 204613 with periods  $1290 \pm 9$  days and  $878 \pm 4$  days respectively (McClure 1997). The estimated  $[C/Fe]$  is  $< 1$  for all objects except for HD 55496. Thus if we follow the CEMP stars classification of Beers and Christlieb (2005) only HD 55496 falls into the CEMP star group with  $[Fe/H] \leq -1.0$  and  $[C/Fe] \geq 1.0$ . Several authors have adopted  $[C/Fe] \geq 0.5$  to define CEMP stars (Ryan et al. (2005), Carollo et al. (2012)). In our sample four objects have  $[C/Fe] \geq 0.5$ . The Objects HD 89668, HD 111721, HD 148897, HD 164922 and HD 167768 give near solar or mildly under solar value for  $[C/Fe]$ . These objects also show near solar or underabundant  $[Ba/Fe]$  value. Although other heavy elements are mildly enhanced in these objects, these objects are unlikely to belong to the group of CEMP or classical CH stars.

We have estimated the Ba abundance for all the objects in our sample, however abundance of Eu could be measured only for four objects. Following the abundance criteria of Beers and Christlieb (2005) based on Ba and Eu abundances two objects HD 104979 and HD 204613 with  $[Ba/Eu] \geq 0.5$ , fall into the group of CEMP-s stars. Both the objects

show enhancement in heavy elements. In HD 104979 the heavy s-process elements are more enhanced than the light s-process elements with  $[hs/lr] \sim 0.18$ . In HD 204613 the light s-process elements are more enhanced with  $[hs/lr] = -0.1$ . The parametric model based analysis indicates higher contribution from the s-process than that of r-process to the abundances of heavy elements observed in these objects.

CH stars are low-mass objects. Eight objects in our sample for which we could estimate stellar masses are found to be low-mass objects with masses in the range  $0.6 M_{\odot}$  to  $1.6 M_{\odot}$ . Stellar masses could not be estimated for the rest four objects as the parallax estimates are not available in the literature. These four objects HD 122202, HD 89968, HD 126681 and HD 164922 have  $[Ba/Fe] < 0.33$  with HD 89968 giving a  $[Ba/Fe]$  estimate of  $\sim -0.24$ . These objects do not qualify as CH stars. Abundance ratios of the sample stars show a large scatter with respect to  $[Fe/H]$  (Figure 14).  $[X/Fe]$  ratios of the heavy elements for most of the objects belonging to group 3 are distinctly lower than their counterparts observed in the stars of group 1 and 2. Abundance ratios of Eu with respect to Fe observed in three stars of group 3 show similar values as those seen in two objects of group 2.

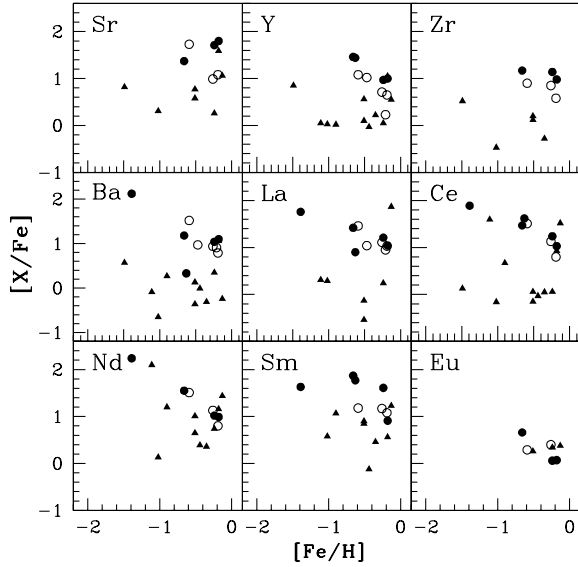
Population I Ba stars are believed to be metal-rich counterparts of CH stars. Both CH stars and Ba stars are known to show enhancement in heavy elements. A comparison of the abundance ratios of heavy elements with those observed in barium stars (solid squares) and CEMP stars from Masseron et al. (2010) (solid pentagons) within the metallicity range 0.2 to  $-2.2$  show that the group 3 objects distinctly return lower  $[X/Fe]$  ( $[Zr/Fe]$ ,  $[Ba/Fe]$ ,  $[La/Fe]$  and  $[Ce/Fe]$ ; Figure 15). These objects do not seem to belong to the group of CH stars as far as the chemical composition of heavy elements are concerned.

#### Acknowledgement

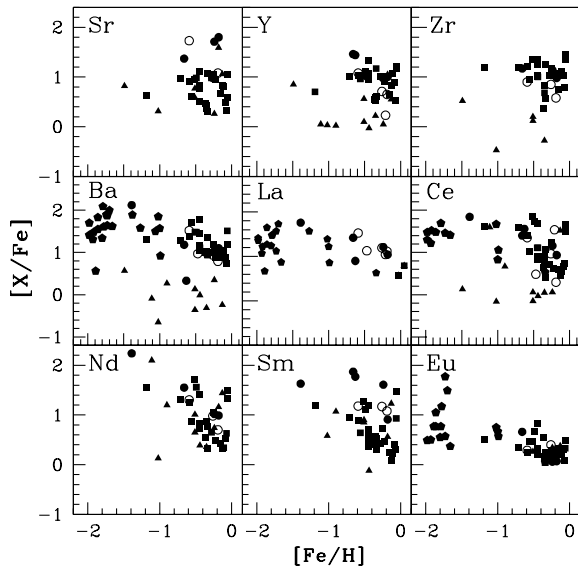
We thank the referee, for valuable comments which have improved our paper considerably. This work made use of the SIMBAD astronomical database, operated at CDS, Strasbourg, France, and the NASA ADS, USA. Fundings from CSIR and DST project No. SB/S2/HEP-010/2013 are gratefully acknowledged.

## REFERENCES

- Abia C., Rebolo R., Beckman J.E., Crivellari L., 1988, A&A, 206, 100
- Allen D. M. & Barbuy B., 2006a, A&A, 454, 895
- Allen D. M. & Barbuy B., 2006b, A&A, 454, 917
- Alonso A., Arribas S., Martinez-Roger C., 1996 A&A, 313, 873
- Alonso A., Arribas S. & Martinez-Roger C., 1999, A&AS, 140, 261
- Aoki, W., Ryan, S. G., Norris, J. E., Beers T. C., Ando H.,



**Figure 14.** Abundance ratios of heavy elements observed in the program stars with respect to  $[\text{Fe}/\text{H}]$ . The confirmed binaries are shown with solid circles, the objects with limited radial velocity information are shown with open circles, and the rest of the objects are indicated with solid triangles. The abundance ratios show a large scatter with respect to metallicity.



**Figure 15.** Estimated abundance ratios of Ba, La, Ce and Eu with respect to Fe are plotted in this figure where solid circles indicates the confirmed binaries, open circles indicate the objects with limited radial velocity information and the solid triangles indicate the rest of the objects in our sample. The abundance ratios are compared with the abundance ratios observed in CEMP stars (solid pentagons) from Masseron et al. (2010) and Ba stars (solid squares) from Allen and Barbuy (2006a).

Iwamoto N., Kajino T., Mathews G. J., Fujimoto M. Y., 2001, *ApJ*, 561, 346

Aoki, W., Norris, J. E., Ryan, S. G., Beers, T. C. & Ando, H., 2002a, *ApJ*, 567, 1166

Aoki, W., Ryan, S. G., Norris, J. E., Beers, T. C., Hiroyasu, A., Tsangarides, S. 2002b, *ApJ*, 580, 1149

Aoki W. et al., 2005, *ApJ*, 632, 611

Aoki, W., Beers, T. C., Christlieb N., Norris, J. E., Ryan, S. G., Tsangarides, S. 2007, *ApJ*, 655, 492

Arlandini et. al., 1999, *ApJ*, 525, 886

Asplund M., Grevesse N., Sauval A. J., 2005, *ASPC*, 336, 25

Baranne A., Queloz D., Mayor M., Adranzyk G., Knispel G., Kohler D., Lacroix D., Meunier J. P., Rimbaud G., Vin A., 1996, *A&AS*, 119, 373

Barbuy B., Spite M., Spite F., Hill V., Cayrel R., Plez B., Petitjean P., 2005, *A&A*, 429, 1031

Bartkevicius A., 1996, *BaltA*, 5, 217

Beers T.C., & Christlieb N., 2005, *ARA&A*, 43, 531

Bidelman W. P., *Astron. J.*, 1981, 86, 553

Bond H. E., 1974, *ApJ*, 194, 95

Busso M., Gallino R., Lambert D. L., Travaglio C., Smith V. V., 2001, *ApJ*, 557, 802

Cavallo R.M., Pilachowski C.A., Rebolo R., 1997, *PASP*, 109, 226

Christlieb N., Green P. J., Wisotzki L., Reimers D., 2001, *A&A*, 375, 366

Carollo et al., 2012, *ApJ*, 744, 195

Frasca A., Covino E., Spezzi L., Alcalá J.M., Marilli E., Fursez G., Gandolfi D., 2009, *A&A*, 508, 1313

Fulbright J.P., 2000, *AJ*, 120, 1841

Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, *A&AS* 141, 371

Gontcharov G.A., 2006, *AstL*, 32, 759

Goswami A. & Prantzos N., 2000, *A&A*, 359, 191

Goswami A., 2005, *MNRAS*, 359, 531

Goswami A., Wako A., Beers T. C., Christlieb N., Norris J., Ryan S. G., Tsangarides S. 2006, *MNRAS*, 372, 343

Goswami A., Bama P., Shantikumar N. S., Devassy D., 2007, *BASI*, 35, 339

Goswami A., Karinkuzhi D. & Shantikumar N. S., 2010a, *MNRAS*, 402, 1111

Goswami A., & Wako A., 2010b, *MNRAS*, 404, 253

Goswami A., & Karinkuzhi D., 2013, *A&A*, 549, 68

Goswami A., Subramania Athiray P, Karinkuzhi D., in *Recent Advances in Spectroscopy: Astrophysical, Theoretical and Experimental Perspectives* eds. Chaudhuri, R. K. et al., *Astrophysics and Space Science Proceedings*, p 211, Springer Verlag, 2010c

Gratton R.G. & Sneden C., 1994, *A&A*, 287, 927

Gratton R.G., Carretta E., Castelli F., 1996, *A&A*, 314, 191

Gratton R.G. & Sneden C., 1991, *A&A*, 241, 501

Gratton R.G., Sneden C., Carretta E., Bragaglia A., 2000, *A&A*, 354, 169

Jonsell K., Barklem P. S., Gustafsson B., Christlieb N., Hill V., Beers T. C., & Holmberg J., 2006, *A&A*, 451, 651

Koleva, M. & Vazdekis, A., 2012, *A&A*, 538, 143

Karinkuzhi D. & Goswami A., 2014, *MNRAS*, 440, 1095

Kyrolainen J., Tuominen I.; Vilhu O., Virtanen H., 1986, *A&AS*, 65, 11

Kurucz R. L., 1995a, in *ASP Conf. Proc. 78, Astrophysical Applications of Powerful New Databases*, ed. S. J. Adelman & W. L. Wiese (San Francisco:ASP), 205

Kurucz R. L., 1995b, in *ASP Conf. Proc. 81, Laboratory and Astronomical High Resolution Spectra*, ed. A. J. Sauval, R. Blomme, & N. Grevesse (San Francisco:ASP), 583

Lambert D. L., & Ries L. M., 1981, *ApJ*, 248, 228

Lawler J. E., BonVallet G., Sneden C., 2001, *ApJ*, 556, 452

Lü, P. K. 1991, *AJ*, 101, 2229

Luck R.E., 1991, *ApJS* 75, 579.

Lucatello S., Gratton R. G., Beers T. C., Carretta E., 2005, ApJ, 625, L833  
 Luck R.E., Bond H.E., 1991, ApJS, 77, 515  
 Luck R.E., & Heiter U, 2007, AJ, 133, 2464  
 Massaroti A., Latham, D.W., Stefanik, R.P., Fogel, J. 2008, AJ, 135, 209  
 Masseron T., Johnson J. A., Plez B., Van Eck S., Primas F., Goriely, S., Jorissen, A. 2010, A&A, 509, A93  
 McClure R. D., 1983, ApJ, 268, 264  
 McClure R. D., 1984, ApJ, 280, L31  
 McClure R. D. & Woodsworth W., 1990, ApJ, 352, 709  
 McClure R. D., 1997, PASP, 109, 536  
 MacConnell D.J., Frye R.L., Upgren A.R., 1972, AJ, 77, 384  
 McWilliam A., 1990, ApJS 74, 1075.  
 McWilliam A., 1998, AJ, 115, 1640  
 Mishenina T.V., Pignatari M., Korotin S.A., Soubiran C., Charbonnel C., et al., 2013, A&A, 552, 128  
 Moultaqa J., Ilovaisky S. A., Prugniel P., Soubiran C., 2004, PASP, 116, 693  
 Nissen P.E. & Schuster W.J., 2011, A&A, 530, 15  
 Nissen P.E., Chen Y.Q., Schuster W.J., Zhao G., 2000, A&A, 353, 722  
 Nidever D.L., Marcy G.W., Butler R.P., Fischer D.A., Vogt S.S., 2002, ApJS, 141, 503  
 Norris J. E., Ryan S.G., Beers, T. C. 1997a, ApJ, 488, 350  
 Norris J. E., Ryan S.G., Beers T. C. 1997b, ApJ, 489, L169  
 Norris J. E., Ryan S.G., Beers T. C., Aoki, W & Ando H., 2002, ApJ, 569, L107  
 North P., Berthet S., Lanz T., 1994, A&A 281, 775  
 North P., & Duquennoy A., 1991, A&A, 244, 335  
 North P., & Duquennoy A., in *Binaries as tracers of stellar formation* eds. Duquennoy A., & Meyer D., 1992, *Cambridge University Press*, p205  
 Pilachowski C.A., Sneden C.; Booth J., 1993, ApJ, 407, 699  
 Prochaska, J. X., & McWilliam A., 2000, ApJ, 537, L57  
 Prugniel P., Vauglin I., Koleva M., 2011, A&A, 531, 165  
 Poubaux et al., 2004, A&A, 424, 727  
 Ramirez I., Melendez J., 2004, ApJ, 609, 417  
 Rebolo R., Molaro P., Beckman J.E., 1988, A&A, 192, 192  
 Ryan S.G., Lambert D.L., 1995, AJ, 109, 2068  
 Ryan S.G., Aoki W., Norris J. E., Beers T. C. 2005, ApJ, 635, 349  
 Siebert et al., 2011, AJ, 141, 187  
 Santos et al., 2011, A&A, 526, 112  
 Smith V.V., Coleman H., Lambert D.L., 1993, ApJ, 417, 287  
 Smith V.V., Coleman H., Lambert D.L., 1993, ApJ, 417, 287  
 Smith V.V., 1984, A&A 132, 326  
 Smith V.V., Lambert D.L., 1986, ApJ 303, 226.  
 Sneden C., 1973, PHD thesis, Univ of Texas at Austin  
 Sneden C.; Lambert D.L.; Pilachowski C.A., 1981, ApJ, 247, 1052  
 Sneden C., McWilliam A., Preston G. W., Cowan J.J., Burris D. L., Armosky B. J., 1996, Apj, 467, 819  
 Sozzetti et al. 2009, ApJ, 697, 544  
 Soubiran C., Bienayme O., Mishenina T.V., KOVTYUKH V.V., 2008, A&A, 480, 91  
 Sousa S.G., Santos N.C., Israelian G., Mayor M., Udry S., 2011, A&A, 533, 141  
 Tomkin J., & Lambert, D.L., 1986, ApJ, 311, 819  
 Tomkin J., Lemke M., Lambert D.L., Sneden C, 1992, AJ, 104, 1568  
 Worley C. C, Hill V., J. Sobeck J., Carretta E., A&A, 2013, 553, A47